Dynamics of Supermassive Black Holes

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In the beginning...

- In the local universe we see SMBHs in almost all galaxies with apparently well defined mass function

- We see AGNs at high redshift

- We don't know how SMBHs formed or their mass growth history

Initial Conditions

- Given hierarchical structure formation we can map galaxy merger trees as function of redshift and halo mass

- We do not know if the SMBH mass scaling is local or applies at early times

- Lower end of halo/SMBH mass range is very poorly constrained - LISA sources

- We see binary black holes locally, as loosely bound post-merger wide binaries
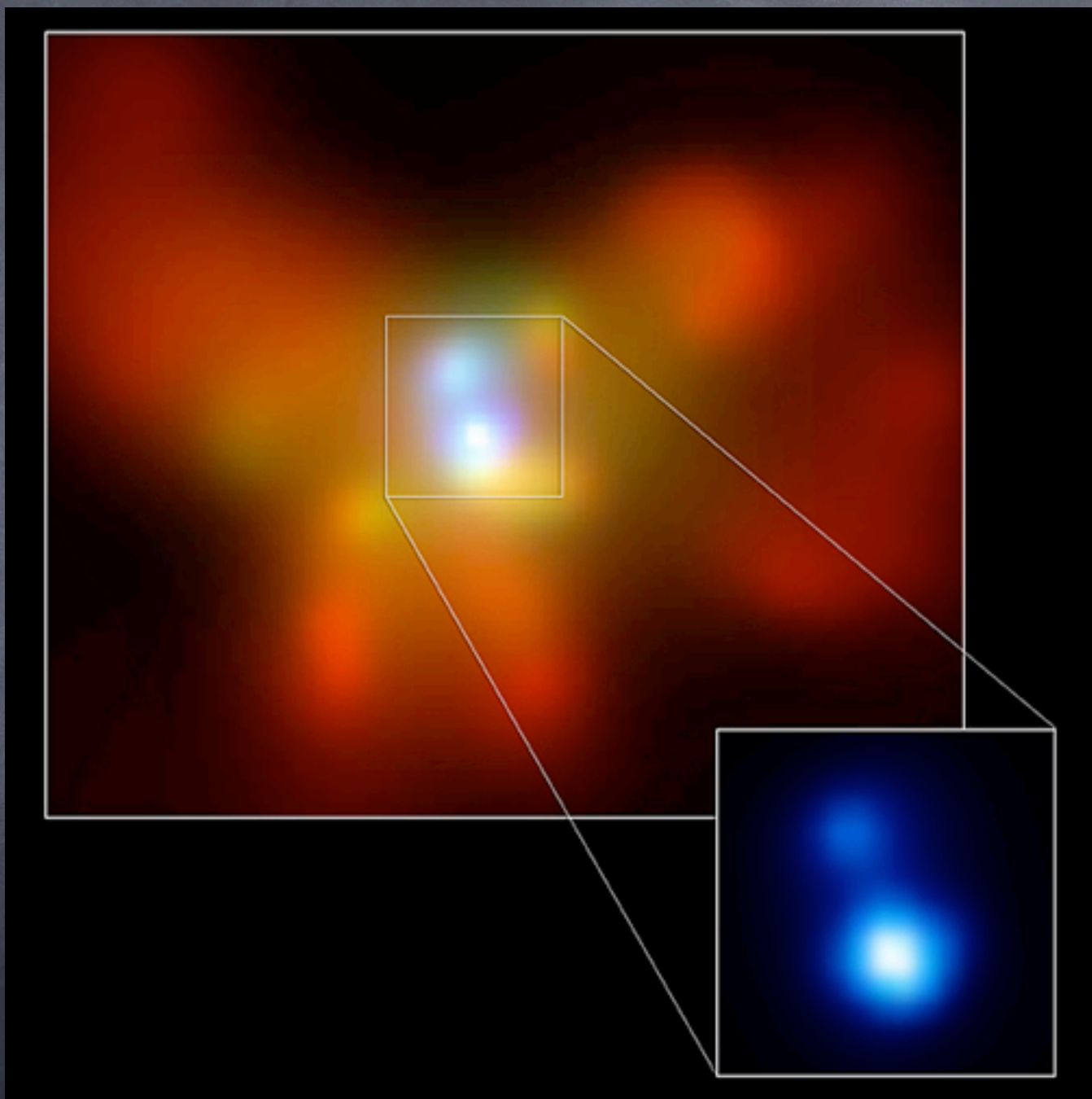
NGC 6240
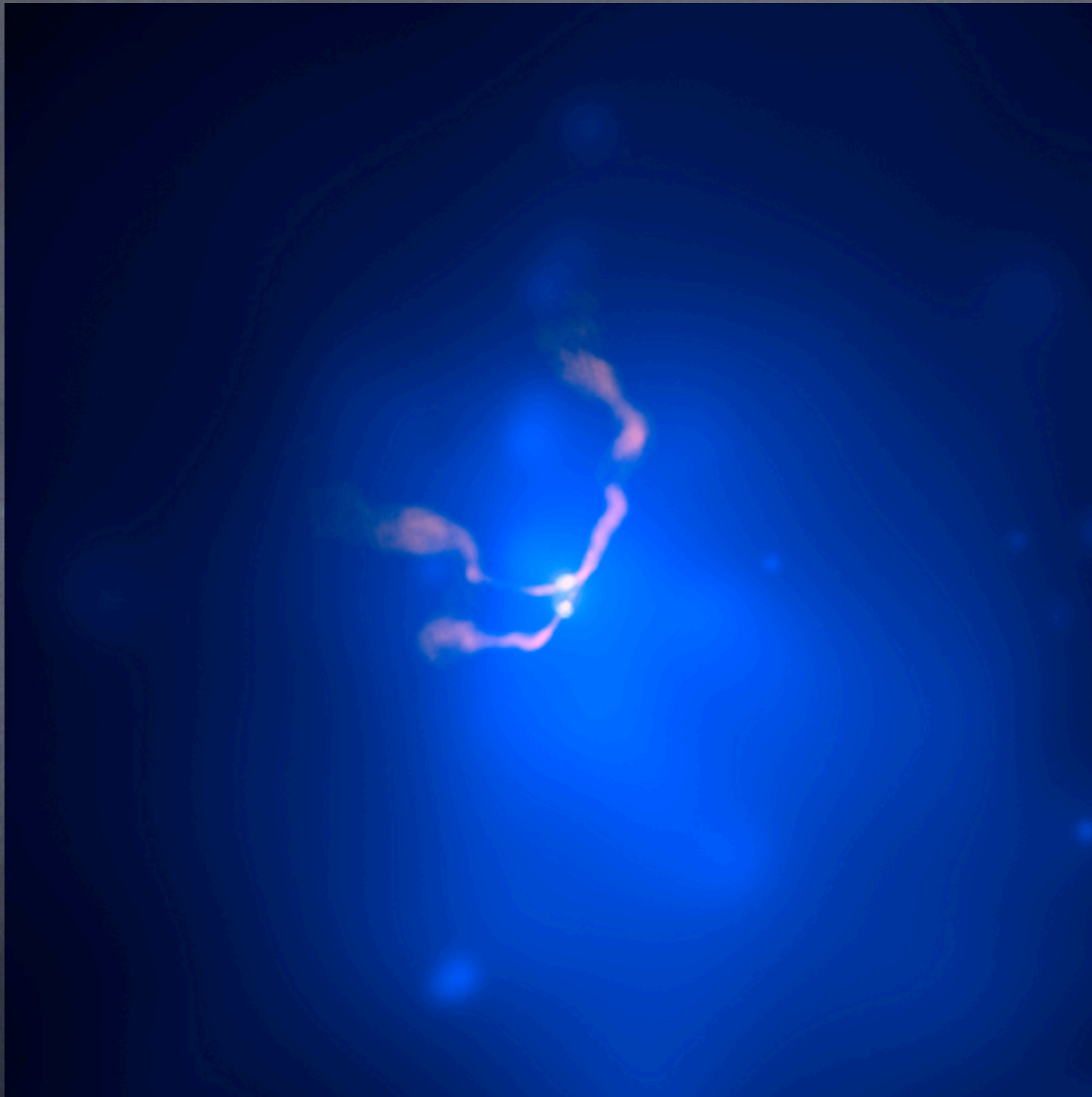
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Grand Mergers

- Mergers of galactic halos deposit SMBH in some wide orbit about the "primary"

- For z >> 1 mergers, we do not understand the accretion history well enough to strongly constrain mergers. Can test extreme range of models (cf Volonteri et al, Sesana et al, Micic et al).

- Expect grand design equal mass mergers to be rare (cf MW vs M31!)

- Are there IMBHs? Pop III IMHs? Where?
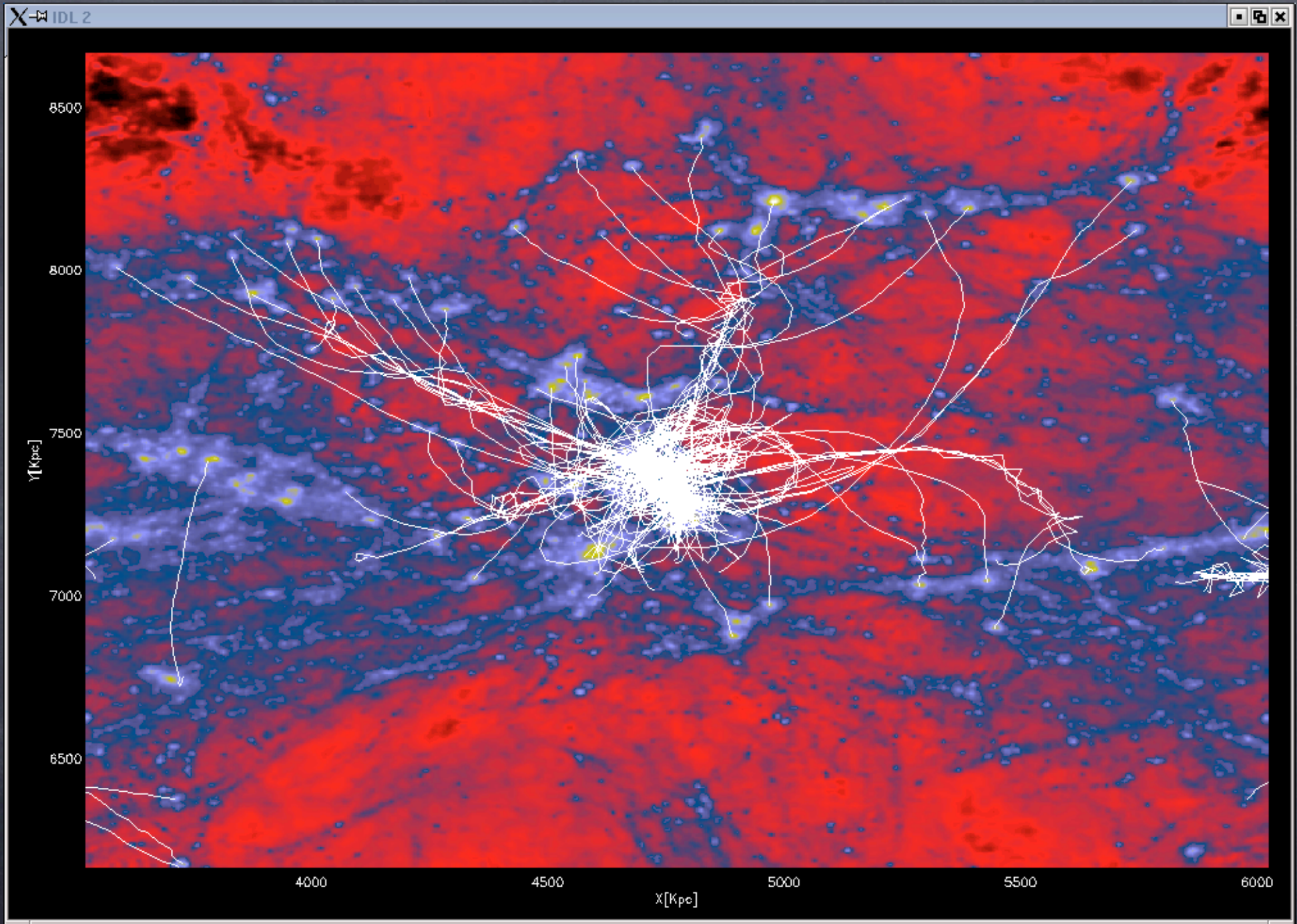
Micic, Abel & Sigurdsson '06

Messy Problem

- Initial Condition:

  two black holes – mass function, associated nucleus of stars, accretion disk

  two galaxies – density, dispersion, shape, morphology, $f(E,J,I_3)$, relaxed?

  Real galaxies are not spherical, merging galaxies particularly not so.

 "Initial" SMBH orbit? Circular from dyn fric?

  Undergoing violent relaxation?

  gas!

  (stellar mass function, ongoing star formation)

Dynamical Friction end-point

- From merger scenarios we need three key pieces of information:
    - Mass ratio (distribution) of SMBH
    - "Initial eccentricity" of the orbit at the point the binary becomes hard. Circularization? No...!
    - Velocity distribution of inner part of merged galaxy, including isotropy
    - dynamical friction: depends on density gradient and dispersion profile
    - low mass SMBHs in halo or outer disk
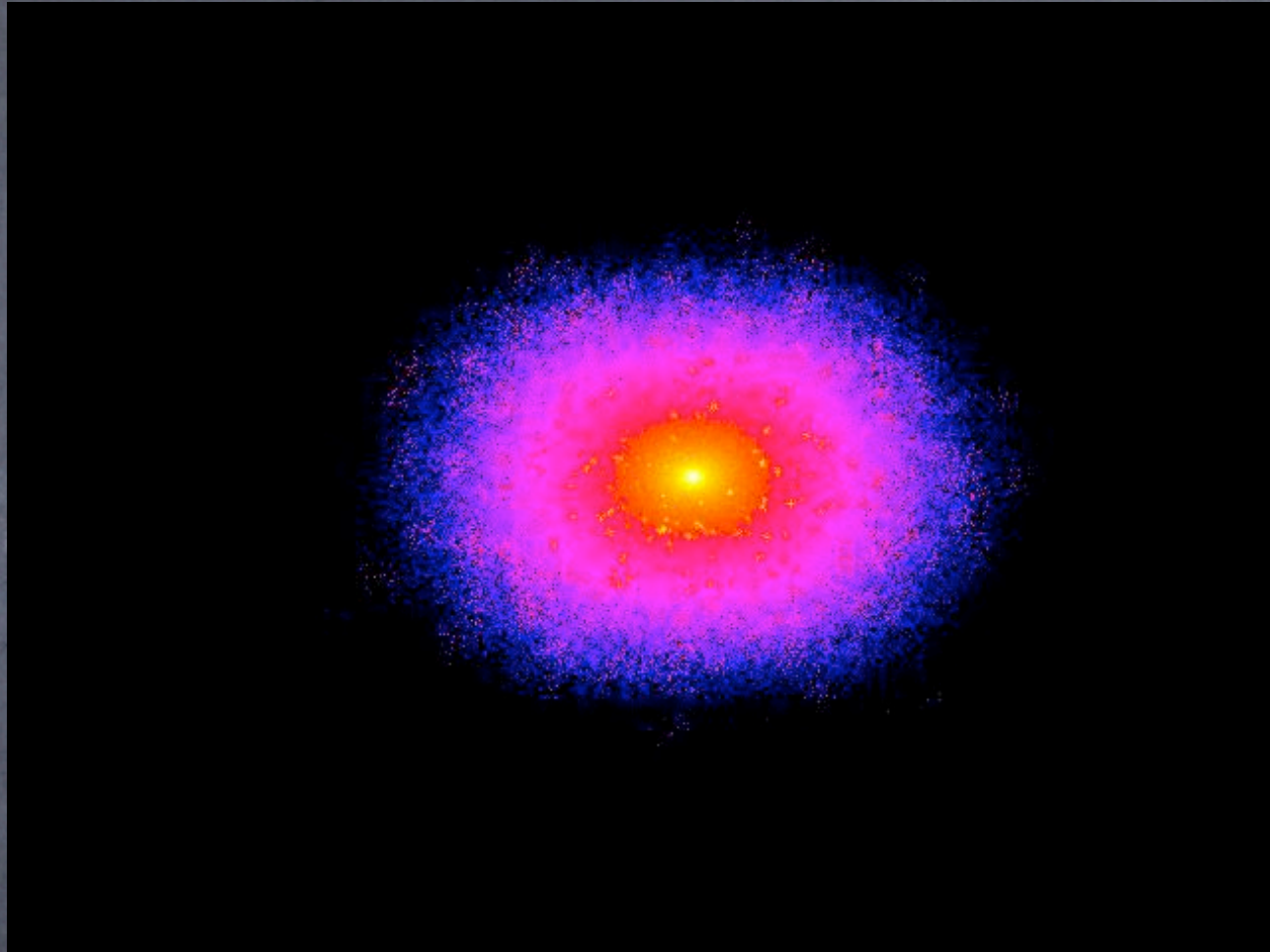
Holley-Bockelmann - final stage galaxy with halos. In general some fraction is on centrophilic orbits

Stellar scattering

- Dynamical friction is collective interaction of SMBH with stellar and CDM background

- At late stages SMBH decouples and interacts strongly with individual stars (cf Merritt & Milosavljevic LRR '05)

- Rapid depletion of inner region and "last parsec" problem

- Inelastic scattering (cf Ivanov et al)

- CDM interaction? Cusp? SIDM??

Is it really a problem

- For near equal mass SMBHs in high end of LISA range, in initially circular orbits in spherical isotropic galaxies

- Not a problem at lower mass or for $M_2 \ll M_1$

- Eccentricity; gas or third SMBH may matter

- Triaxial or chaotic orbits avert last parsec (cf Berczik et al; Holley-Bockelmann et al)

Eccentric behaviour

- Can we take away J faster than E?

- How.

- Does it help enough to matter?
  - $t_{gr} \propto a^4 f(e)$ - $f(e) \sim 2(1-e^2)^{7/2}$
  - If final e >~ 0.9 then we don't need to harden through the difficult last stages through further encounters. We must resolve this issue and whether it is initial condition dependent or not.
  - harmonics during GW circularisation are at higher f - affects detection prospects if eccentricity persists

Trivia

- de/dt = 0; de/dt < 0; or, de/dt > 0 !

- If e=0; then de/dt => 0

- If e=1 and E << 0; then de/dt <= 0

- In practise appears de/dt not a simple interpolation function with a single maximum on the interval

- The interesting physics may come from the hardest parts of the simulations

- Formally <dE/dt*J - E*dJ/dt> determines sign of de/dt (cf Vecchio et al '94)

History

- Roos '81: merger possible if galaxies cuspy, sees de/dt > 0 for large initial e
- Mikkola & Valtonen: de/dt depends on initial e and f(v)
- Vecchio et al: de/dt > 0; analytic
  - soft binary e is frozen (e/(de/dt) > a/(da/dt))
  - hard binary - runaway e growth
- Fukushige et al: initial e is high
- Phinney & Villumsen: initial small e remains small

Modern age

- Quinlan '96; Quinlan & Hernquist '97:
  - $de/dt > 0$ for high initial e
  - In Jaffe and Plummer N-body models, $e \rightarrow 0$ including initially anisotropic models
  - scatterring shows $de/dt > 0$; N-body shows $e \rightarrow 0$
- Milosavljevic & Merritt '01: $e \rightarrow 0$ - 32k Nbody with Jaffe cusp
- Hemsendorf et al '02: e grows - numerical effect?
- Aarseth '02: e grows strongly
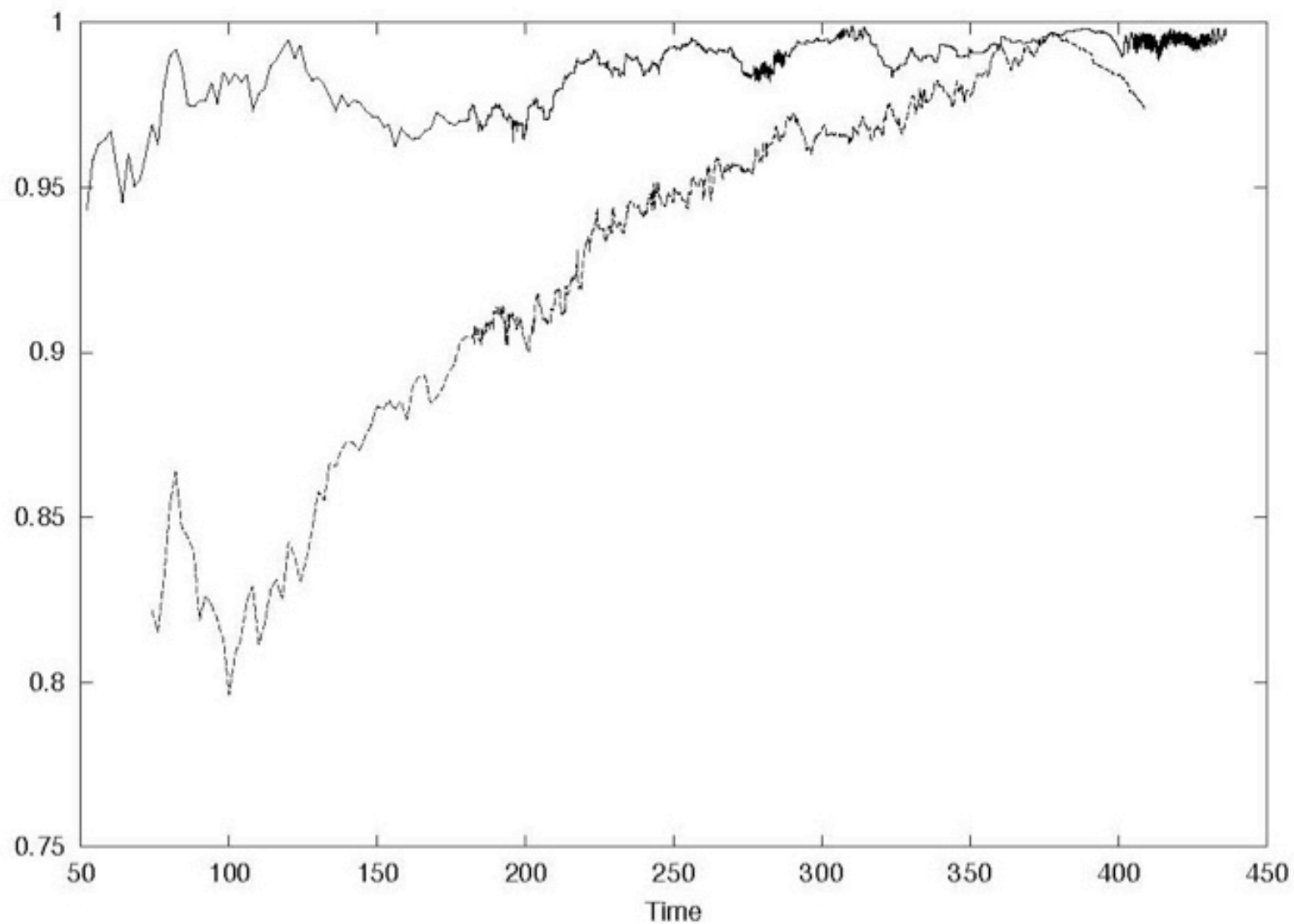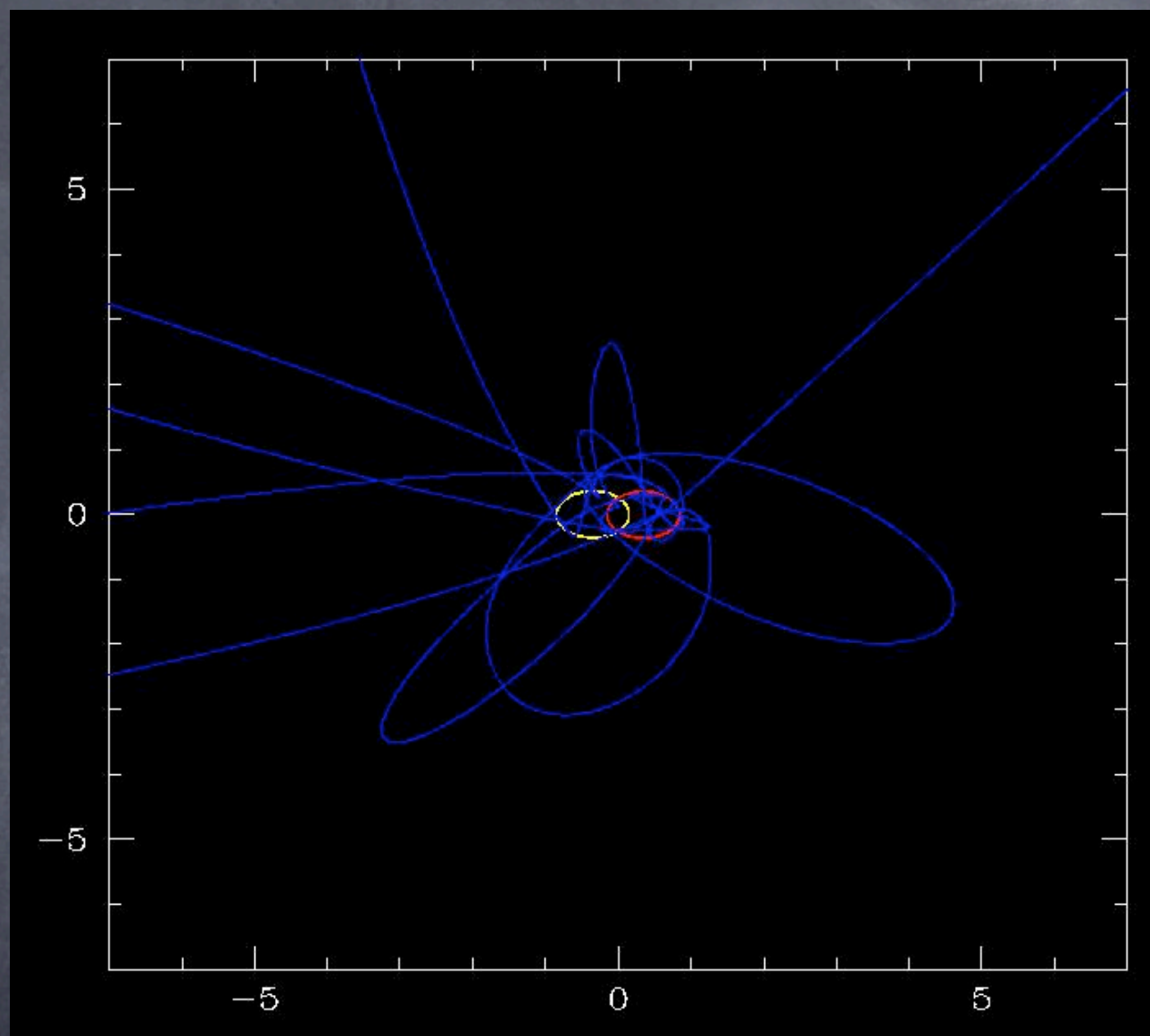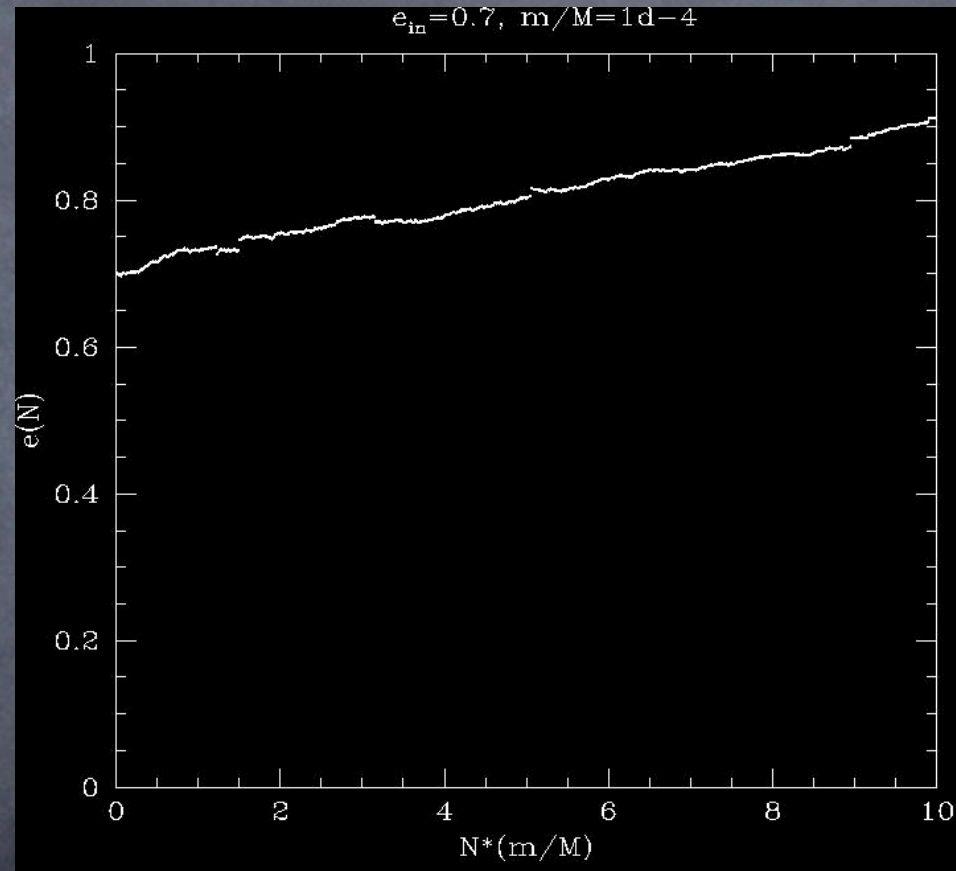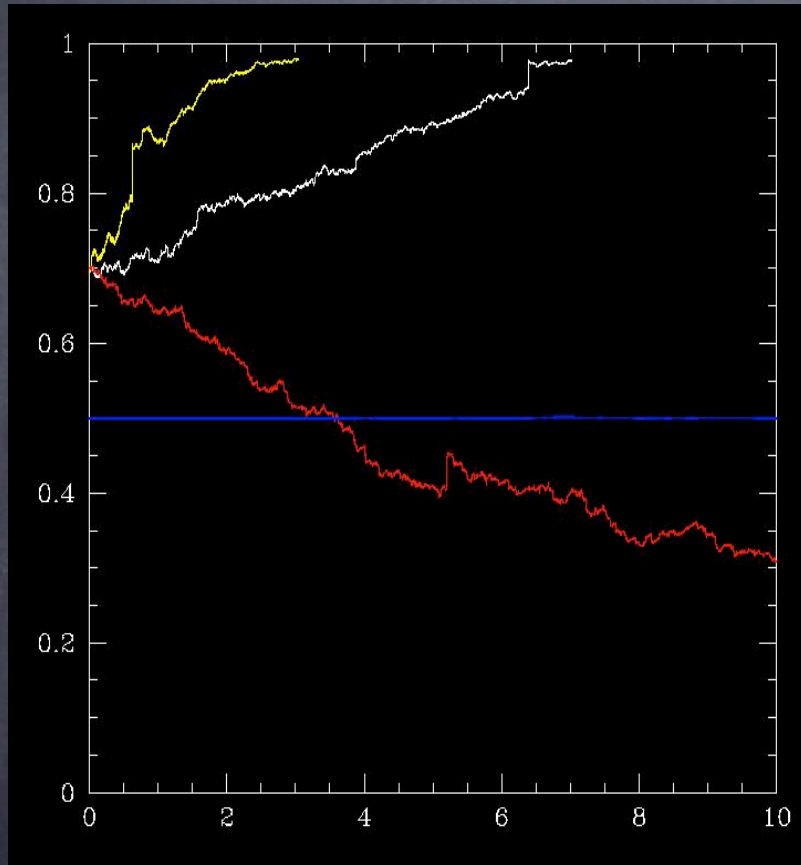- Makino et al '04 - de/dt inconclusive, find dE/dt depends on N still

Figure 2. Eccentricity evolution of BH binaries. The upper curve is for $N = 1.2 \times 10^5$ and the lower curve for $N = 2.4 \times 10^5$.

Aarseth '03

More scatterings

Eccentricity

- e(N) for scattering
- Low J scatterers
- High J scatterers
- m/M = 0.001

Note largish jumps in eccentricity especially at high eccentricity

Resonance dominated, small N a concern

Not just what you do, but how you do it...

- If high J* matters, then diffusion vs pinhole filling matters a lot. Shape and $f(E,J)$ matters.

- Violent relaxation, triaxiality, or large scale coarseness are significant

- BH wandering from super-elastic recoil (cf Merritt, Chatterjee et al). Depleted core implies no restoring force and large wandering amplitude.

- What if M_1 not at density maximum?

- Star formation and dissipation?

What causes eccentricity?

- Dynamical friction regime:

  - central density minima !

  - radial anisotropy (too large - unstable?)

  - $m_2 \ll m_1$

- 3-body regime: low J stars increase e

  - how stars re-enter loss cone matters!

  - diffusive l-c => e -> 0

  - e_0 large => $\langle de/dt \rangle > 0$

Signatures

- Hyper velocity stars (Brown et al) - in Milky Way and local group - something interesting in the MW centre?

- Hyper velocity, high metallicity IC* and Planetary Nebulae; different IC* population, metal rich and younger than bulk - may be few % and kinematically distinct (Holley-Bockelmann et al '06). Seen already?
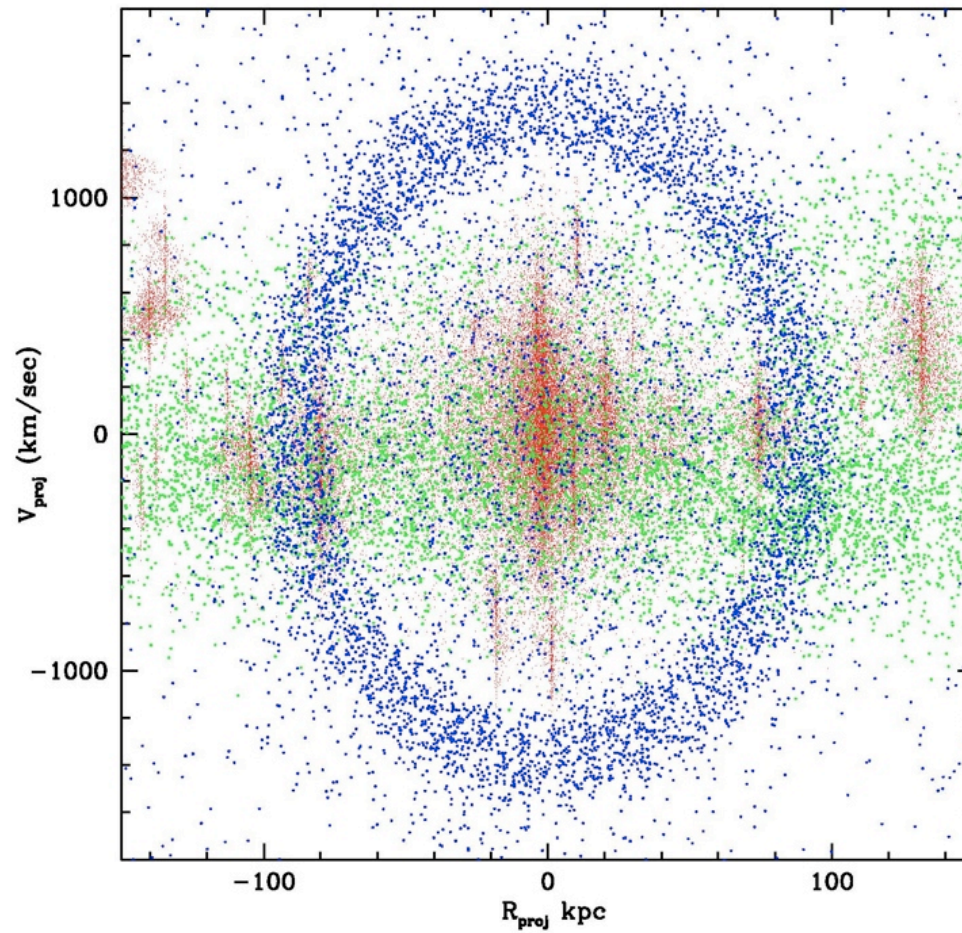
Holley-Bockelmann et al '06

When gravity fails

- Gas dynamics: BBR noted that if we wait long enough gas will arrive. cf Armitage & Natarajan 2001, 2005 Escala et al 2003, 2004; Dotti et al - eccentricity?

- If AGN for ~ Salpeter time, then M_{gas} ~ M at radius $r < t_S(\alpha c_S)$ ~ few pc or less

- BH spin flip (cf Wilson & Colbert '95)
  - spin up during coalescence due to accretion?
  - GPS sources???

- If gas fails, we will merge again. Full blown 3-body SMBH interactions and recoil.

- Residual worry: grav rad recoil ejects BH at coalescence - especially in low mass dwarf galaxies

Signatures

- Post-merger signature (Milosavljevic & Phinney)

- Pre-merger signature - Bogdanovic et al
  Find local population of close SMBHBs before gravitational radiation regime - LISA precursor systems, get census and parameters from synoptic surveys

Second merger

- Core vs Cusp - second merger of high mass may fail because of low density left from previous merger

- Also gas poor in general

- But... orbits are not isotropic anymore - may get eccentricity growth

Triples

- If SMBHs get stuck may have long lived moderately wide binaries

- See in situ

- Or third SMBH comes along (cf Valtonen et al).

- Ejection through triple interaction

- Kozai pumping of eccentricity

- Most likely for gas poor massive galaxies

Conclusion

- Most scenarios now optimistic about event rate of SMBH mergers

- Mass ratios very uncertain; dependent on gas accretion history – LISA resolves this?

- Binary SMBHs may drive bright QSOs (NB LISA sources llAGNs not QSOs)

- Lot of secondary issues and astrophysics